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INSIDE THE CONE OF PROTECTION

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Although lightning cones of protection and cones of attraction have been used for over 100 years, much confusion still remains as to their effectiveness, particularly as applied to personnel protection. At Kennedy Space Center, a 1:1 cone of protection with a straight side is standard for structure or equipment protection. However, at the launch pad, where a 400-foot lightning lightning rod on top of an insulating mast is used for pad lightning protection, the idea developed that personnel within a 400-foot radius of this mast would be safe from lightning and those outside it would not. Since it is obvious that a person 395 feet (120.4 m.) from the mast is only slightly safer than one at 405 feet (123.5 m.), an investigation was initiated to calculate the probabilities of a person being struck by lightning as he moves closer to the mast inside the cone of protection. Since the risk does not go to zero outside the structure, the risk level can then be estimated.

Golde, Pierce, and others have presented data and probability curves from which the probability of striking a person standing within the cone of protection can be calculated. The striking distance theory, dating back to the time of Ben Franklin, can be used to define a cone of protection with a circular side and the attraction radius about a tower and an individual about 6 feet in height. The striking distance is a function of stroke charge which in turn is realated to stroke peak current.

To arrive at the expected strike frequency, it was necessry to measure the strike frequencies at KSC. Krider and others have found a mean area density of cloud-to-ground lightning at KSC of about 4.6 ± 3.1 flashes per km^2 per month in the summer. An overall frequency is estimated as about 20 flashes per km^2 per year. With these data, the risk of exposure at various distances from the lightning mast can be calculated. Assuming continuous exposure during thunderstorms, this risk varies from about one strike per person in 1,400 years near the tower to one stroke per person in 300 years at about 400 foot (122 m.).

Since exposure is not continuous, the risk is less for individuals who are only temporarily exposed; however, since many workers may be present, the risk of accident is greater. If a person is exposed to lightning in an open area such as on a golf course in Florida through one complete storm, the risk of being struck is about the same as being killed in a motor vehicle accident, about once in 4,000 years. In the vicinity of a 400-foot (122 m.) tower, the risk is reduced by a factor of about 33 at a distance of 150 feet (46 m.) from the tower.

PERSONNEL LIGHTNING PROTECTION outside but near tall structures is a concern at Kennedy Space Center (KSC). Standards relating to the protection of the Shuttle vehicle, equipment, and small nearby structures invoke the 1:1 cone of protection (1)* with a straight side where the radius of the circle of protection on the ground equals the height of the structure and is centered at the center of the structure. In the case of the lightning mast on the top of the Fixed Service Structure (FSS), the height is about 400 ft. (122 m.) resulting in a circle of protection on the ground with a radius of 400 ft. (122 m.). The immediate question which arises is: "How safe are personnel from the lightning strike hazard inside this circular area?" Obviously, a person just inside this boundary is about as exposed as a person just outside it. Many protection cone shapes have been proposed (1), but none of them function as a shield against lightning. They all describe a geometric probability boundary within which the probability of being struck by lightning is very low. Systematic investigations of the protection afforded by a vertical lightning rod have concluded that no specific protective zone could be ascribed with complete confidence (1). It is the purpose of this paper to illustrate how the probabilities of strokes to personnel within, as well as outside, the cone of protection vary and can be estimated so that the risk may be evaluated relative to the penalties or risks involved in not performing a particular activity requiring exposure.

BASIC ASSUMPTIONS

The geometrical approach to the solution for the probability of a person being struck by lightning near a tall structure will be used for this analysis. The lightning leader is assumed to progress from uniformly distributed charged regions in the cloud toward the earth in steps until its tip is close enough to strike the ground or a grounded object in one final jump. The height of the leader tip at this critical breakdown point is termed the "striking distance" (1). This concept dates back to Benjamin Franklin (1767). During the process, a streamer also is formed on the structure or other point on the ground and grows toward the leader. The leader and streamer meet at a junction point about 1/3 of the distance from the streamer initiating terminal to the "point of influence" on the stepped leader (2). The stepped leader moves downward in a random manner until it is within striking distance of the ground. The lightning then strikes the closest ground point. A typical stroke to the top of the lightning mast on the FSS is shown in Fig. 1 where the striking distance was estimated as about 700 ft. (213 m.).

*Numbers in parentheses designate References at end of paper.

The fundamental geometry for a tall structure of height H and a striking distance of S_d is shown in Fig. 2. All leaders that arrive first at a distance S_d from the tall structure when all other distances from it to ground points are greater than S_d are assumed to strike the structure. For the calculated results, the height of the FSS mast, which is 400 ft. (122 m.), is the tall structure height. Similarly, it is assumed that all strokes whose leaders arrive first at a distance of S_d from a standard 6-ft. (1.83 m.) person will strike the person. As shown in Fig. 2, the result is that, for a particular S_d, all strokes within a "radius of attraction" R will be attracted to the tall structure or person and therefore cannot reach the ground within this radius. The radius of attraction is a function of the striking distance (3):

$$R = (S_d^2 - (S_d - H)^2)^{1/2}$$

$$R = H((2S_d/H) - 1)^{1/2} \qquad (1)$$

R may also be considered the radius protected by the tall structures against strokes with a particular S_d to persons or small structures on the ground. The area protected from strikes is a linear function of S_d:

$$A = \pi H(2S_d - H) \qquad (2)$$

and if $S_d >> H$

$$A \simeq 2\pi H S_d$$

The above formulas hold for $S_d \geq H$. If $S_d < H$, then $R = S_d$ and $A = \pi S_d^2$.

The striking distance is a function of the charge in the leader tip which, in turn, is related to the peak current, I_{pk}, in the return stroke. To take into account the fact that upward streamers from a tall structure may be as long as a few hundred meters (4) and that S_d should increase with structure height, the curve giving the largest striking distance for various peak currents was selected for the 400-ft. (122 m.) tower calculations (Golde, Fig. 6) (1). A tower height of less than 150 m. is not likely to trigger lightning with an upward going leader (4). The measurement of the probability of strokes having various peak currents vary widely and a composite of the results of several investigators was used in the next section. The data was divided into 10 deciles of 10 percentiles each and an average striking distance and average peak current was assigned to each decile.

For calculating strikes to a person, a more conservative relationship between striking distance and peak current was used which was expressed by a formula due to Love (1):

$$S_d = 10\ I_{pk}^{0.65}\ \mathrm{m} \qquad (3)$$

Krider and others (5) have estimated a mean monthly area flash density at KSC over the years from 1974 to 1980 of 12 discharges/ km^2/month in June, July, and August. The number of cloud-to-ground discharges was estimated as 4.6/km^2/month. Using the seasonal distribution of thunderstorms at KSC (6) for extrapolation, the yearly average is about 20 cloud-to-ground discharges/km^2/year. This density was used to find the stroke probabilities per year in the next section.

RESULTS

In a manner similar to that used in Reference (7), the results of the calculations for a 400-ft. (122 m.) tower and for a 6-ft. (1.83 m.) person are tabulated in Tables 1 and 2. I_{pk} and S_d are average values of peak current and average striking distances respectively selected from the curves and formula referenced in the previous section. R is the attraction radius. It is assumed that all strokes of the specified magnitude will be attracted to the tower within that radius and therefore they will not hit the ground or a person on the ground. The estimated stroke density of 20 strokes/km^2/year is equivalent to 2 x 10^{-6} strokes/m^2/year/ decile used for these calculations. The probabilities for each average current in a decile of hitting the tower are summed to obtain the cumulative probability of strokes, below the specified average magnitude, hitting the tower. As the strokes become larger, S_d and the attraction area increase so that more large strokes are attracted to the tower than small strokes. Small stroke leaders must arrive close to the tower by chance in order to strike it. The estimated cumulative probability for all strokes of 2 per year is about what has been experienced at KSC.

Similar calculations may be made for a 6-ft. (1.83 m.) person. According to the results, an exposed person could attract large strokes from 92 ft. (28 m.) away. If the person raises a 3-ft. (0.915 m.) golf club over his head, increasing his total height to 9 ft. (2.74 m.), the attraction radius increases by 20 ft. to 112 ft. (34.2 m.). As we have shown, where S_d>>H, the attraction area is proportional to H for a particular S_d. Therefore, the 50% height increase due to the golf club results in a 50% greater chance of being hit by lightning. This is why it is so important to maintain a low profile on a beach, golf course, or other exposed area.

Tables 1 and 2 show that, as a person moves toward the tower from a distance of about 915 ft. (279 m.), he is initially protected only against the larger strokes which can hit the tower and then against smaller and smaller strokes. At 377 ft. (115 m.) or about 400 ft. (122 m.), a person is protected against strokes ≥17.6 kA and must wait 294 years, on the average to be struck, being sure to be exposed to all 97 thunderstorms per year. However, it should be pointed out that the size of the stroke is not of interest to the person being struck. If the person is not near the tower, a person might be struck once every 41.5 years. The probability may be reduced by a factor of 7 by approaching to within 377 ft. (115 m.) of the tower. Finally, at a distance of 150 ft. (46 m.), the probability is reduced to once per 1,364 years, providing a factor of 33 compared to unprotected exposure. Tables 1 and 2 illustrate that the protection gradually increases as the distance from the tower decreases with no sharp boundaries. Currently, the tendency is to reduce to allowed radius of protection where personnel are concerned. For example, Lee (2) suggests a radius of 50 ft. (15.2 m.). It may be more logical to accept the risk in certain circumstances, particularly under the conditions discussed in the next section.

Since the launch pad radius is about 1,500 ft. (457 m.), at a cloud-to-ground stroke density of 20 strokes/km^2/year, it is estimated that about 13 strokes would hit the launch pad per year. If two hit the FSS mast and one hits the nearby water tower, about 10 strokes/ year are left to hit elsewhere on the launch pad.

CONDITIONAL PROBABILITIES

So far, we have assumed unrealistic conditions. For example, we have assumed full exposure to all thunderstorms, symmetrical approach from all angles, uniform strike density distribution, and a fixed average ratio between cloud-to-cloud and cloud-to-ground strokes. It is hoped that in the future, we will be able to take advantage of more specific conditions.

It is obvious that no one will be exposed to lightning in all the storms so that a factor must be introduced to account for exposure time, such as the exposure time divided by the total thunderstorm minutes per year. Using Krider's 107 minutes per storm on the average in the summer (5), by extrapolation, KSC storms would last about 107 minutes x 97 storms/year = 10,000 minutes (about one week)/year. The minutes are not of equal threat value and therefore should be weighted in real time in conformance to the actual storm intensity and locations. Storms are located over the threatened area only a portion of the time. At KSC, thunderstorms generally approach from the westerly directions. If the charged areas can be located and the direction of approach determined, specific probabilities may be calculated. For example, if the charged areas are west of the launch pad, personnel working east of the tower are much less threatened. The cloud-to-ground stroke probability should also be related to charge location. Some storms in Florida produce

almost all cloud-to-cloud lightning which is much less of a threat to personnel, even if located overhead. When we can confidently predict specific conditions, the lightning hazard can be more specifically estimated.

CONCLUDING DISCUSSION

While the hazard of being struck by lightning is small, it is comparable to the hazards of being killed by tornadoes, floods, and earthquakes combined. If a person is required to be exposed to the lightning hazard in the vicinity of a tall structure, the degree of hazard can be estimated. The concept of striking distance provides a technique, as has been illustrated. While the estimate will vary with the assumptions and data used, it is evident that the probability does not vary suddenly at a particular distance from the tower. However, the probability of being struck does decrease rapidly as the tower is closely approached.

The probability of an individual being killed in an automobile accident is about 24 deaths/100,000 people/year or once in 4,167 years for a person. From the results in Tables 1 and 2, if we assume that an individual is exposed to only one complete Florida storm/year and is located at a distance of 377 ft. (115 m.) from a 400-ft. (122 m.) tower, the person would be struck by lightning every 97 x 294 = 28,518 years since his exposure is reduced to 1/97 of that previously calculated. At the outer 915 ft. (279 m.) distance, the probability would be once every 41.5 x 97 = 4,025 years or about the same chance as being killed in an auto accident. Since, nationally, the chances of being killed by lightning are less than those of being killed by a motor vehicle by a factor of about 500, most people try not to expose themselves to the lightning strike hazard, even for the equivalent of one complete storm per year. Further, from a safety point of view, the probability of any lightning strike to a group of persons is important. This hazard is increased by the number of people exposed.

The hope for reducing the lightning strike hazards in the future lies in our ability to make specific predictions about the location of the thunderstorm charged regions and about the thunderstorm intensity and other characteristics that may be used to accurately predict the strike threat to personnel at specific locations.

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Table 1 - Probability of Striking a 400 ft (122 m) Tower

Decile	$\overline{I}_{pk}$	$\overline{Sd}$ m	$\overline{R}$ m	Area m^2	Decile Probability Strokes/Year	Cumulative Probability Strokes/Year	Years/Strike
0- 10	6.2 kA	46	46	6,648	0.01330	0.01330	75.2
10- 20	12.9 kA	90	90	25,447	0.05089	0.06419	15.6
20- 30	17.6 kA	115	115	41,548	0.08310	0.14729	6.8
30- 40	22.7 kA	137	136	58,107	0.11621	0.2635	3.8
40- 50	28.4 kA	161	156	76,454	0.15291	0.4164	2.4
50- 60	35.2 kA	186	174	95,115	0.19023	0.6066	1.65
60- 70	44.5 kA	217	195	119,459	0.23892	0.8455	1.18
70- 80	57.0 kA	258	219	150,674	0.30135	0.1468	0.872
80- 90	77.0 kA	318	250	196,350	0.39270	1.5395	0.65
90-100	112.0 kA	380	279	244,545	0.48909	2.0286	0.49

Table 2 - Probability of Striking a 6 ft (1.83 m) Person

Decile	$\overline{I}_{pk}$	$\overline{Sd}$ m	$\overline{R}$ m	Area m^2	Decile Probability Strokes/Year	Cumulative Probability Strokes/Year	Years/Strike
0- 10	6.2 kA	32.7	10.8	366	0.000732	0.000732	1,364
10- 20	12.9 kA	52.7	13.8	598	0.001196	0.001928	519
20- 30	17.6 kA	64.5	15.3	735	0.001470	0.003398	294
30- 40	22.7 kA	76.1	16.6	866	0.001732	0.005130	195
40- 50	28.4 kA	88.0	17.9	1,007	0.002014	0.007144	140
50- 60	35.2 kA	101.2	19.2	1,158	0.002316	0.009460	106
60- 70	44.5 kA	117.9	20.7	1,346	0.002692	0.012152	82
70- 80	57.0 kA	138.5	22.4	1,576	0.003152	0.015304	65
80- 90	77.0 kA	168.4	24.8	1,932	0.003864	0.019168	52
90-100	112.0 kA	214.8	28.0	2,463	0.004926	0.024094	41.5

FIGURE CAPTIONS

Fig. 1 - A typical lightning stroke to the top of the lightning mast, Pad-39A, KSC

Fig. 2 - Geometry for determining the radius of attraction for lightning strokes to a tall structure or person